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Palladium-Catalyzed Oxidative Cross-Coupling of Conjugated Enynones with Organoboronic Acids

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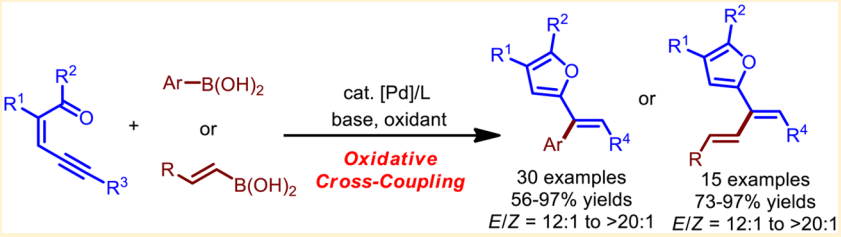
Supporting Information



ABSTRACT: A palladium-catalyzed oxidative cross-coupling reaction of conjugated enynones with organoboronic acids is developed. This reaction provides an efficient methodology for the synthesis of functionalized furan derivatives, including 2-alkenylfurans and furan-substituted 1,3-dienes. Palladium−carbene migratory insertion is proposed as the key step in these transformations. Notably, the β-hydride elimination process occurs in a stereoselective manner, resulting in the formation of double bonds with high (*E*)-selectivity.

INTRODUCTION

Diazo compounds (and their precursors *N*-tosylhydrazones) have recently emerged as a new type of coupling partner in Pd-catalyzed reactions.[1] In these transformations, the diazo compounds (or *N*-tosylhydrazones) normally serve as nucleophilic coupling partners to react with electrophiles,[2] while oxidative cross-couplings[3] between nucleophilic carbene precursors and nucleophiles are also known.[4] On the other hand, conjugated enynones have been employed as furyl carbene precursors in transition-metal-catalyzed reactions.[5] In these reactions, the furyl metal carbene is proposed as the key intermediate and subsequent classical carbene transformations may occur, affording a good approach for the synthesis of furan derivatives (Scheme 1a).[6]

We have recently demonstrated that such conjugated enynones could act as carbene precursors in the Pd-catalyzed cross-coupling reactions with electrophiles. DFT calculations indicate that Pd carbene migratory insertion is involved in the reaction (Scheme 1b).[7,8] The reaction constitutes an efficient approach for the synthesis of 2-alkenylfuran derivatives, the polymers of which have been used as biorenewable surrogates for polystyrenes.[9] As a continuation of our interest in carbene-involved cross-coupling reactions, we report herein the Pd-catalyzed oxidative cross-couplings of conjugated enynones with nucleophiles, including aryl- and alkenylboronic acids (Scheme 1c).[10] The reaction produces the corresponding furyl-substituted olefins and conjugated dienes in good yields and in a stereoselective manner.

RESULTS AND DISCUSSION

At the outset, we investigated the reaction of conjugated enynone **1a** with 4-tolylboronic acid **2** (Scheme 2a). As expected, the target product **3a** was obtained in high yield under the optimized reaction conditions.[11] To our delight, this oxidative cross-coupling reaction affords high (*E*)-selectivity, and the configuration of the formed double bond is confirmed by NOESY experiments.[11] On the contrary, in our previous report, the corresponding coupling with aryl bromide gave essentially no selectivity (Scheme 2b).[7] Thus, the oxidative cross-coupling shows advantages over the normal coupling reactions with electrophiles in terms of both yield and stereoselectivity.

Encouraged by these results, we then proceeded to screen the scope of this reaction. First, a variety of conjugated enynones **1a−o** were examined to react with *p*-tolylboronic acid **2** under the optimized reaction conditions (Scheme 3). It should be noted that the enynones used in this study should have at least one hydrogen on the carbon of the substituent (R) adjacent to the alkyne moiety, in which β-hydride elimination process could occur to realize the catalytic cycle. When R is a pentyl group, the enynones derived from symmetric or unsymmetric 1,3-dicarbonyl compounds all show decent reactivity, affording the corresponding products in excellent yields and with good selectivity (**3a−d**). When the moiety R bears phenyl or benzyloxy, similar results are obtained (**3e−h**).

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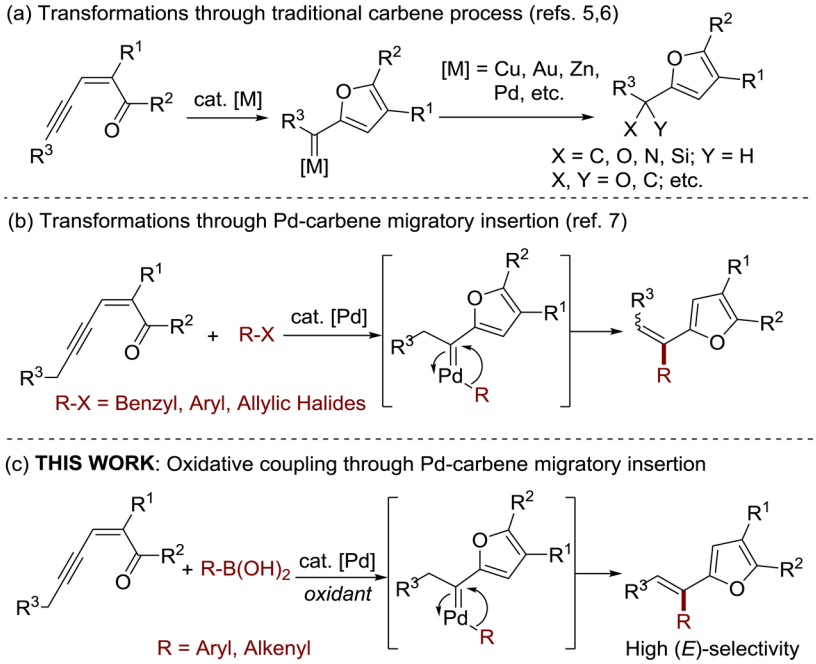
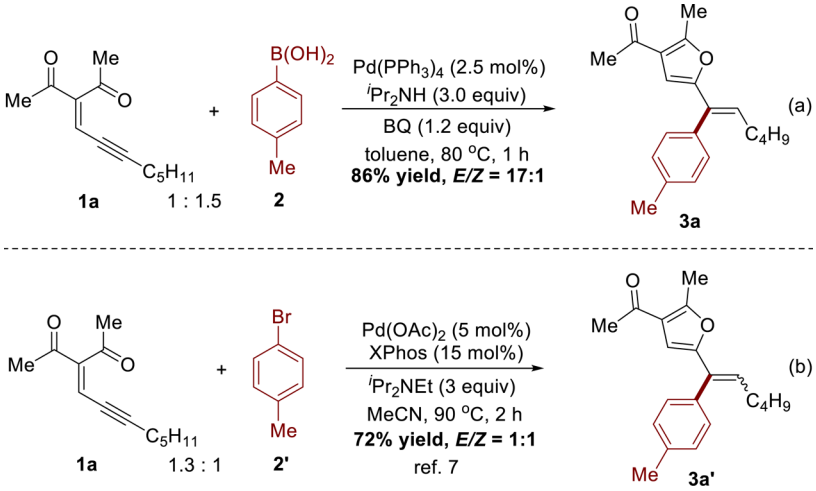
Scheme 1. Transition-Metal-Catalyzed Reaction of Conjugated Enynones through Furyl Carbene Intermediate



Scheme 2. Pd-Catalyzed Reaction of Conjugated Enynone 1a in Oxidative and Normal Cross-Couplings (BQ = 1,4-Benzoquinone)



Enynones bearing a secondary alkyl group lead to the formation of tetrasubstituted olefins in good yields (**3i**–**l**). In addition, a terminal olefin can also be obtained through this reaction (**3m**). Notably, the second carbonyl moiety on the enynones is not integrant for this reaction (**3n**,**o**), although the yield and selectivity is diminished in the case of **3o**.

Next, by employing enynone **1b** as the substrate, a series of arylboronic acids **2a**–**o** were tested under the same reaction conditions (Scheme 4). Arylboronic acids bearing *para*- (**4b**–**f**), *meta*- (**4g**–**i**), as well as *ortho*- (**4j**,**k**) substituents all participate in this reaction smoothly, affording the corresponding furan products with good to excellent yields and excellent (*E*)-selectivity. It is noteworthy that the halide substituents are compatible with this Pd-catalyzed transformation (**4e**,**f**,**h**). Moreover, this reaction is also applicable to the fused aromatic (**4l**,**m**) and heteroarylboronic acids (**4n**,**o**), although the latter afforded slightly diminished yields.

The reaction was also extended to alkenylboronic acids. As shown in Scheme 5, a range of alkenylboronic acids **5a**–**e** reacted smoothly with enynones under the same reaction conditions, affording the corresponding furyl-substituted conjugated dienes in good to excellent yields with (*E*,*E*)-selectively. *E*-Styrylboronic acid **5a** was first employed to react with a series of enynones, producing the conjugated dienes bearing tri or tetra substituents on the newly formed double bonds (**6a**–**j**). The configuration of the formed double bond in **6c** is confirmed by the NOESY experiment.[11] Again, the additional carbonyl group in enynone is not necessary, as shown in the case of **6j**. The substituents on the styrylboronic acids show little influence on this transformation (**6k**,**l**), and the 2-alkyl-substituted alkenylboronic acids can also smoothly participate in this reaction (**6m**–**o**).

On the basis of our previous studies,[4a,7,8] a plausible mechanism has been proposed for the Pd-catalyzed oxidative

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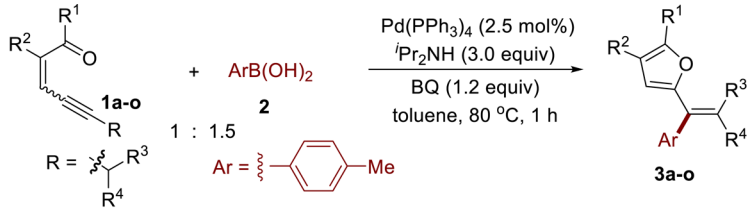
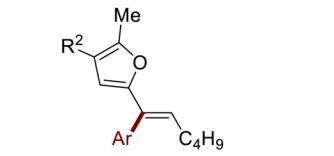
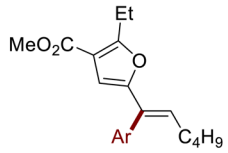
Scheme 3. Scope of the Reaction of Enynones with *p*-Tolylboronic Acid 2[a,b]

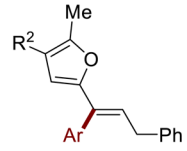




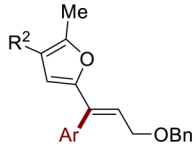
3a, R^2 = COMe, 86%, *E*/*Z* = 17:1[c]
3b, R^2 = CO_2Et, 91%, *E*/*Z* = 18:1
3c, R^2 = $CO_2{}^tBu$, 92%, *E*/*Z* = 16:1



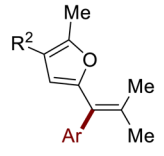
3d, 95%, *E*/*Z* = 16:1



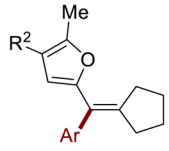
3e, R^2 = COMe, 77%, *E*/*Z* = 18:1
3f, R^2 = CO_2Me, 78%, *E*/*Z* = 17:1



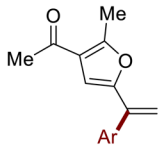
3g, R^2 = COMe, 83%, *E*/*Z* > 20:1
3h, R^2 = CO_2Me, 78%, *E*/*Z* > 20:1



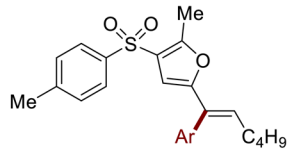
3i, R^2 = CO_2Et, 80%
3j, R^2 = $CO_2{}^tBu$, 86%



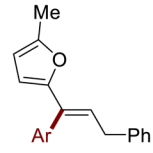
3k, R^2 = COMe, 80%
3l, R^2 = CO_2Me, 82%



3m, 75%



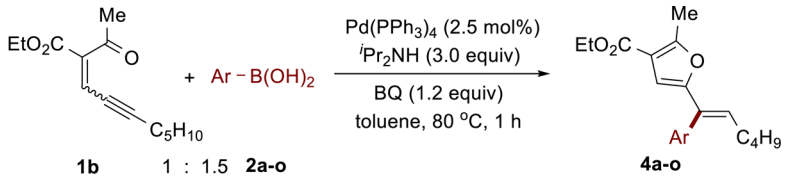
3n, 75%, *E*/*Z* = 20:1



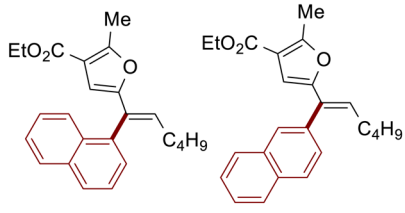
3o, 56%, *E*/*Z* = 12:1

[a]Yield of isomers by column chromatography. [b]The *E*/*Z* ratio was determined by ^{1}H NMR. [c]The configuration of the formed double bond was confirmed by the NOESY experiment.

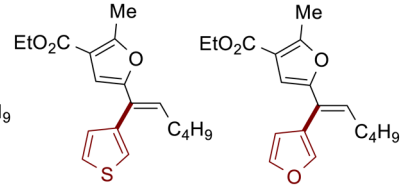
Scheme 4. Scope of the Reaction of Arylboronic Acids with Enynone 1b[a,b]



4a, Ar = C_6H_5, 87%, *E*/*Z* = 19:1
4b, Ar = *p*-$MeOC_6H_4$, 72%, *E*/*Z* = 15:1
4c, Ar = *p*-$MeO_2CC_6H_4$, 80%, *E*/*Z* = 17:1
4d, Ar = *p*-AcC_6H_4, 69%, *E*/*Z* = 17:1
4e, Ar = *p*-ClC_6H_4, 84%, *E*/*Z* = 15:1
4f, Ar = *p*-BrC_6H_4, 81%, *E*/*Z* = 15:1
4g, Ar = *m*-$MeOC_6H_4$, 90%, *E*/*Z* = 17:1
4h, Ar = *m*-BrC_6H_4, 70%, *E*/*Z* = 15:1
4i, Ar = *m*-MeC_6H_4, 97%, *E*/*Z* = 17:1
4j, Ar = *o*-$MeOC_6H_4$, 88%, *E*/*Z* = 17:1
4k, Ar = *o*-MeC_6H_4, 94%, *E*/*Z* = 16:1



4l, 88%, *E*/*Z* > 20:1 **4m**, 88%, *E*/*Z* = 17:1



4n, 65%, *E*/*Z* = 13:1 **4o**, 63%, *E*/*Z* = 17:1

[a]Yield of isomers by column chromatography. [b]The *E*/*Z* ratio was determined by ^{1}H NMR.

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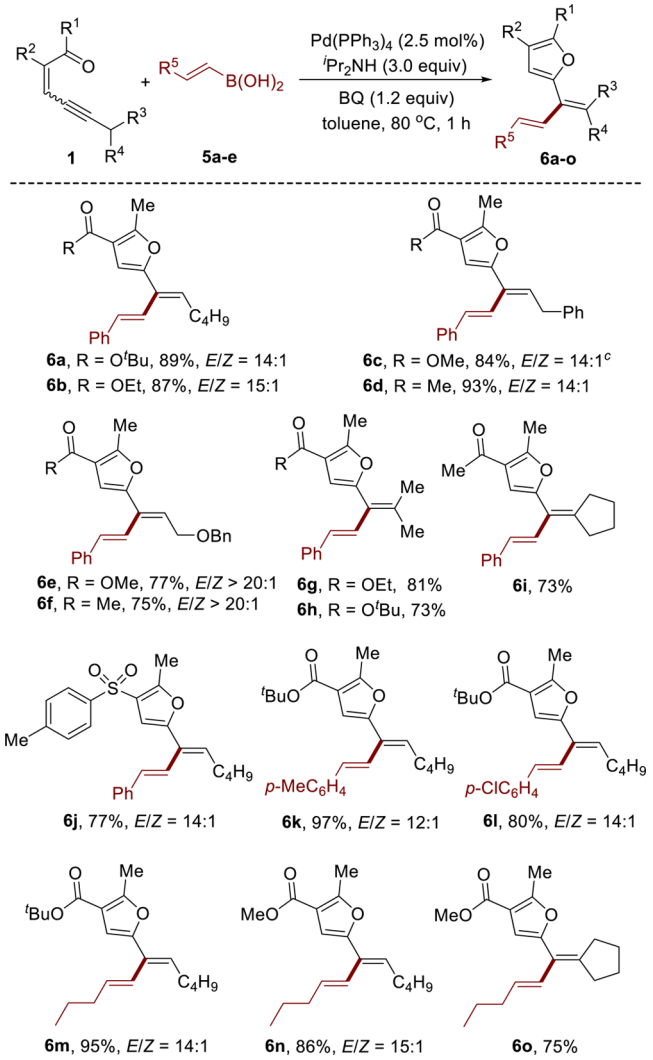
Scheme 5. Pd-Catalyzed Coupling of Enynones with Alkenylboronic Acid[a,b]

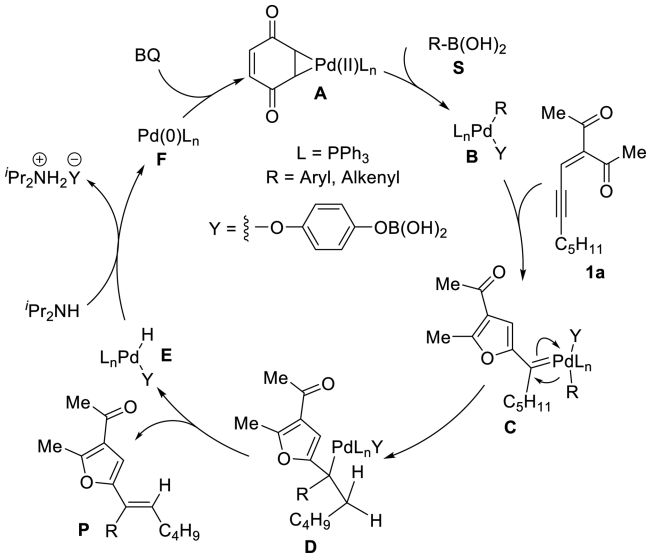


[a]Yield of isomers by column chromatography. [b]The *E*/*Z* ratio was determined by ^{1}H NMR. [c]The configuration of the formed double bond is confirmed by the NOESY experiment.

cross-coupling reaction (Scheme 6). Since the reaction is initiated by Pd(II) species **A**, the Pd(0) precatalyst should be first oxidized to Pd(II) by 1,4-benzoquinone.[4a] Subsequent transmetalation with organoboronic acid **S** affords organopalladium(II) intermediate **B**, which activates the alkyne moiety of enynone **1a** to form furyl Pd−carbene species **C**. Then, migratory insertion of the Pd−carbene occurs to form intermediate **D**, which undergoes *β*-hydride elimination to produce **P** as the final product. The generated Pd(II) species **E** converts to Pd(0) species **F** through reductive elimination with the aid of the base. Finally, the catalytic reactive Pd(II) species **A** is regenerated through reoxidation to realize the catalytic cycle.

The high (*E*)-selectivity of this reaction is attributed to the selective *β*-hydride elimination (**D** to **E**) according to the proposed mechanism. However, currently it is difficult to explain the high (*E*)-selectivity because there is no significant difference on the steric size between the aryl or alkenyl and the furyl moiety in the transition state of the *cis* *β*-H elimination

Scheme 6. Proposed Reaction Mechanism



from intermediate **D**.[7] Further rigorous studies are needed to elucidate this stereoselectivity.

CONCLUSION

In conclusion, we have developed a novel Pd-catalyzed oxidative cross-coupling reaction employing conjugated enynones as the carbene precursors. Aryl- and alkenylboronic acids can be successfully employed as coupling partners in this reaction. The furyl-substituted olefins[12] and conjugated dienes can be obtained, respectively, in good yields and with high (*E*)-selectivity. Further studies will focus on the explanation of the reaction selectivity and development of novel cross-coupling reactions using conjugated enynones as carbene precursors, and these results will be reported in due course.

EXPERIMENTAL SECTION

General Methods. All of the palladium-catalyzed reactions were performed under nitrogen atmosphere in a flame-dried reaction tube. All solvents were distilled under nitrogen atmosphere prior to use. Toluene, dioxane, and THF were dried over Na with benzophenone−ketyl intermediate as indicator. MeCN and MeOH were dried over CaH_2. ^{1}H and ^{13}C NMR spectra were recorded at 400 and 100 MHz. Chemical shifts are reported in ppm using tetramethylsilane as internal standard when using $CDCl_3$ as solvent. IR spectra are reported in wave numbers, cm^{-1}. For HRMS measurements, the mass analyzer is FT-ICR. PE = petroleum ether, EA = ethyl acetate.

General Procedure for Preparation of the Enynones. The conjugated enynones **1a−o** were synthesized by the procedure described in our recent report.[7,8,10] A typical procedure for the synthesis of enynone **1a** is as follows: 1-Heptyne (960 mg, 10 mmol) was dissolved in dry THF (15 mL), and the solution was cooled to −40 °C under nitrogen. *n*-Butyllithium (1.6 M in hexanes, 6.8 mL, 11 mmol) was added dropwise over 2 min while the temperature was maintained between −35 and −40 °C. After completion of the addition, anhydrous DMF (1.55 mL, 20 mmol) was added in one portion, and the cold bath was removed. The reaction system was allowed to warm to room temperature and stirred for 30 min. The reaction mixture was carefully poured into a vigorously stirred biphasic solution prepared from an aqueous solution of KH_2PO_4 (30 mmol in 50 mL H_2O) and Et_2O (30 mL) and cooled over ice to ca. 5 °C. Layers were separated, and the organic extract was washed with water (2 × 30 mL). The combined aqueous layers were back-extracted with Et_2O (30 mL). The combined organic layers were dried over Na_2SO_4 and filtered. Then solvent was removed in vacuo carefully under 0 °C

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to leave a crude acetylenic aldehyde.[13] The crude acetylenic aldehyde was then dissolved in THF (8 mL), and 1,3-dicarbonyl compound acetoacetone (1.0 g, 10 mmol) was added into the solution. Then AcOH (120 mg, 2 mmol) and $MgSO_4$ (240 mg, 2 mmol) were added to the reaction mixture. The mixture was stirred at room temperature for about 1 h. When the reaction was completed as monitored by TLC, filtration through Celite and removal of the solvent by rotary evaporation gave the crude product. The enynone **1a** was purified by chromatography on silica gel with the appropriate mixture of PE and EA (PE:EA = 50:1):[14] yellow oil; 70% yield for two steps (1.44 g); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.70 (t, J = 2.4 Hz, 1H), 2.47 (s, 3H), 2.44 (dt, J = 2.4, 7.1 Hz, 2H), 2.32 (s, 3H), 1.61−1.53 (m, 2H), 1.41−1.30 (m, 4H), 0.91 (t, J = 7.1 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 201.3, 195.8, 149.5, 123.2, 110.5, 76.8, 31.0, 30.9, 27.7, 27.2, 22.1, 20.2, 13.9. The unsymmetric 1,3-dicarbonyl compounds would afford enynones (**1b−d,f,h−j,l**) as a mixture of *E*- and *Z*-isomers in an approximately 1:1 ratio (see the SI for the structures). The enynones need to be kept in the refrigerator below 0 °C.[7,8,10]

General Procedure for Pd-Catalyzed Oxidative Cross-Coupling. Under air atmosphere, $Pd(PPh_3)_4$ (5.8 mg, 0.005 mmol, 2.5 mol %), 1,4-benzoquinone (26 mg, 0.24 mmol), and boronic acid (**2** or **5**, 0.30 mmol) were successively added to a flame-dried 10 mL Schlenk tube. The reaction flask was degassed three times with nitrogen, and dry toluene (2.0 mL) was added using a syringe. Then ^{i}Pr$_2$NH (0.60 mmol, 61 mg) and enynone (**1**, 0.20 mmol) was added by syringe successively. The reaction was heated at 80 °C with stirring for 1 h, cooled to room temperature, and filtered through a short plug of silica gel with PE/EA (PE:EA = 5:1, 10 mL) as eluent. Solvent was then removed in vacuo to leave a crude mixture that was purified by silica gel column chromatography to afford pure product furyl-substituted olefins **3** or **4** or conjugated dienes **6**.

*(E)-1-(2-methyl-5-(1-p-tolylhex-1-en-1-yl)furan-3-yl)ethan-1-one (**3a**):* yellow oil; yield 86% (51 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21 (d, J = 7.8 Hz, 2H), 7.12 (d, J = 7.8 Hz, 2H), 6.26 (t, J = 7.7 Hz, 1H), 5.91 (s, 1H), 2.61 (s, 3H), 2.40 (s, 3H), 2.28 (s, 3H), 2.04 (q, J = 7.5 Hz, 2H), 1.41−1.26 (m, 4H), 0.84 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.3, 157.6, 153.4, 137.1, 134.0, 130.7, 129.49, 128.9, 127.9, 122.7, 107.1, 31.9, 29.1, 28.5, 22.3, 21.2, 14.4, 13.9; HRMS (ESI, m/z) calcd for $C_{20}H_{25}O_2$ $[M + H]^+$ 297.1849, found 297.1850; LRMS (EI, m/z) 296 (M^+, 97), 281 (50), 253 (100), 225 (24), 165 (23); IR (film) 820, 948, 1232, 1580, 1677 cm^{-1}.

*Ethyl (E)-2-methyl-5-(1-p-tolylhex-1-en-1-yl)furan-3-carboxylate (**3b**):* colorless oil; yield 91% (59 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.19 (d, J = 7.9 Hz, 2H), 7.12 (d, J = 8.0 Hz, 2H), 6.22 (t, J = 7.7 Hz, 1H), 5.92 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.56 (s, 3H), 2.38 (s, 3H), 2.04 (q, J = 7.5 Hz, 2H), 1.42−1.26 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.2, 158.3, 153.5, 137.0, 134.1, 131.0, 129.6, 128.9, 127.6, 114.9, 107.5, 60.0, 32.0, 28.5, 22.3, 21.2, 14.4, 13.9, 13.9; HRMS (ESI, m/z) calcd for $C_{21}H_{27}O_3$ $[M + H]^+$ 327.1955, found 327.1954; LRMS (EI, m/z) 326 (M^+, 100), 311 (64), 283 (86), 237 (100), 195 (52); IR (film) 776, 1083, 1232, 1716, 2957 cm^{-1}.

*tert-Butyl (E)-2-methyl-5-(1-p-tolylhex-1-en-1-yl)furan-3-carboxylate (**3c**):* colorless oil; yield 92% (65 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18 (d, J = 7.9 Hz, 2H), 7.11 (d, J = 7.9 Hz, 2H), 6.25 (t, J = 7.7 Hz, 1H), 5.95 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.39 (s, 3H), 2.03 (q, J = 7.7 Hz, 2H), 1.49 (s, 9H), 1.42−1.24 (m, 4H), 0.84 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 163.6, 157.6, 153.2, 137.0, 134.1, 131.0, 129.5, 128.9, 127.4, 116.3, 107.8, 80.4, 32.0, 28.5, 28.3, 22.32, 21.2, 13.9; HRMS (ESI, m/z) calcd for $C_{23}H_{31}O_3$ $[M + H]^+$ 355.2268, found 355.2268; LRMS (EI, m/z) 354 (M^+, 48), 283 (54), 255 (100), 237 (29), 57 (28); IR (film) 778, 1084, 1165, 1366, 1710 cm^{-1}.

*Methyl (E)-2-ethyl-5-(1-p-tolylhex-1-en-1-yl)furan-3-carboxylate (**3d**):* colorless oil; yield 95% (62 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18 (d, J = 7.8 Hz, 2H), 7.11 (d, J = 8.0 Hz, 2H), 6.24 (t, J = 7.7 Hz, 1H), 5.96 (s, 1H), 3.74 (s, 3H), 3.03 (q, J = 7.6 Hz, 2H), 2.38 (s, 3H), 2.04 (q, J = 7.5 Hz, 2H), 1.43−1.26(m, 7H), 0.84 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.4, 163.4, 153.5, 137.0, 134.1, 131.0, 129.5, 128.9, 127.5, 113.6, 107.5, 51.1, 32.0, 28.6, 22.4, 21.3, 21.2, 13.9, 12.4; HRMS (ESI, m/z) calcd for $C_{21}H_{27}O_3$ $[M + H]^+$ 327.1955, found 327.1952; LRMS (EI, m/z) 326 (M^+, 79), 311 (60), 283 (100), 251 (57), 195 (54); IR (film) 779, 1042, 1093, 1234, 1720 cm^{-1}.

*(E)-1-(2-Methyl-5-(3-phenyl-1-p-tolylprop-1-en-1-yl)furan-3-yl)-ethan-1-one (**3e**):* yellow oil; yield 77% (51 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28−7.16 (m, 9H), 6.43 (t, J = 7.8 Hz, 1H), 5.97 (s, 1H), 3.39 (d, J = 7.8 Hz, 2H), 2.59 (s, 3H), 2.41 (s, 3H), 2.28 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.2, 157.9, 153.1, 140.6, 137.5, 133.5, 131.5, 129.6, 129.2, 128.5, 128.4, 126.1, 125.6, 122.8, 108.0, 35.0, 29.1, 21.3, 14.5; HRMS (ESI, m/z) calcd for $C_{23}H_{23}O_2$ $[M + H]^+$ 331.1693, found 331.1692; LRMS (EI, m/z) 330 (M^+, 74), 315 (100), 165 (26), 115 (21), 91 (31); IR (film) 699, 820, 947, 1233, 1678 cm^{-1}.

*Methyl (E)-2-Methyl-5-(3-phenyl-1-p-tolylprop-1-en-1-yl)furan-3-carboxylate (**3f**):* yellow oil; yield 78% (54 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.16 (m, 9H), 6.41 (t, J = 7.8 Hz, 1H), 6.02 (s, 1H), 3.74 (s, 3H), 3.39 (d, J = 7.8 Hz, 2H), 2.57 (s, 3H), 2.39 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.4, 158.7, 153.2, 140.6, 137.4, 133.5, 131.6, 129.5, 129.1, 128.5, 128.4, 126.0, 125.2, 114.6, 108.3, 51.2, 35.0, 21.2, 13.8; HRMS (ESI, m/z) calcd for $C_{23}H_{23}O_3$ $[M + H]^+$ 347.1642, found 347.1652; LRMS (EI, m/z) 346 (M^+, 65), 331 (100), 271 (28), 215 (30), 91 (24); IR (film) 777, 821, 1088, 1234, 1718 cm^{-1}.

*(E)-1-(5-(3-(Benzyloxy)-1-p-tolylprop-1-en-1-yl)-2-methylfuran-3-yl)ethan-1-one (**3g**):* yellow oil; yield 83% (60 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.25 (m, 5H), 7.17 (dd, J = 8.0 Hz, 21.6 Hz, 4H), 6.44 (t, J = 7.0 Hz, 1H), 6.06 (s, 1H), 4.44 (s, 2H), 4.04 (d, J = 7.0 Hz, 2H), 2.61 (s, 3H), 2.40 (s, 3H), 2.29 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.0, 158.4, 152.4, 138.2, 137.8, 136.4, 133.6, 132.8, 129.3, 129.0, 128.2, 127.7, 127.5, 122.8, 109.1, 72.3, 67.1, 29.0, 21.2, 14.4; HRMS (ESI, m/z) calcd for $C_{24}H_{25}O_3$ $[M + H]^+$ 361.1798, found 361.1796; IR (film) 698, 737, 950, 1071, 1678 cm^{-1}.

*Methyl (E)-5-(3-(benzyloxy)-1-p-tolylprop-1-en-1-yl)-2-methylfuran-3-carboxylate (**3h**):* yellow oil; yield 78% (59 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.25 (m, 5H), 7.15 (dd, J = 7.8 Hz, 19.4 Hz, 4H), 6.42 (t, J = 7.0 Hz, 1H), 6.10 (s, 1H), 4.44 (s, 2H), 4.05 (d, J = 7.0 Hz, 2H), 3.75 (s, 3H), 2.60 (s, 3H), 2.39 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.3, 159.3, 152.5, 138.3, 137.7, 133.7, 132.9, 129.3, 128.9, 128.3, 127.7, 127.5, 122.4, 114.8, 109.5, 72.2, 67.2, 51.2, 21.2, 13.8; HRMS (ESI, m/z) calcd for $C_{24}H_{24}NaO_4$ $[M + Na]^+$ 399.1567, found 399.1567; IR (film) 698, 777, 1088, 1233, 1719 cm^{-1}.

*Ethyl 2-methyl-5-(2-methyl-1-p-tolylprop-1-en-1-yl)furan-3-carboxylate (**3i**):* colorless oil; yield 80% (48 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.14 (d, J = 7.8 Hz, 2H), 7.03 (d, J = 8.0 Hz, 2H), 6.15 (s, 1H), 4.24 (q, J = 7.1 Hz, 2H), 2.53 (s, 3H), 2.36 (s, 3H), 2.09 (s, 3H), 1.71 (s, 3H), 1.31 (t, J = 7.1 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.3, 157.6, 153.4, 137.6, 136.2, 134.2, 129.7, 128.8, 126.4, 114.3, 109.7, 59.9, 23.3, 22.5, 21.2, 14.3, 13.9; HRMS (ESI, m/z) calcd for $C_{19}H_{23}O_3$ $[M + H]^+$ 299.1642, found 299.1640; LRMS (EI, m/z) 298 (M^+, 100), 283 (14), 269 (31), 165 (24), 115 (17); IR (film) 777, 1060, 1093, 1232, 1716 cm^{-1}.

*tert-Butyl 2-methyl-5-(2-methyl-1-p-tolylprop-1-en-1-yl)furan-3-carboxylate (**3j**):* colorless oil; yield 86% (56 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13 (d, J = 7.8 Hz, 2H), 7.03 (d, J = 8.0 Hz, 2H), 6.12 (s, 1H), 2.50 (s, 3H), 2.35 (s, 3H), 2.07 (s, 3H), 1.71 (s, 3H), 1.52 (s, 9H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.3, 157.6, 153.4, 137.6, 136.2, 134.2, 129.7, 128.8, 126.4, 114.3, 109.7, 59.9, 23.3, 22.5, 21.2, 14.3, 13.9; HRMS (ESI, m/z) calcd for $C_{21}H_{27}O_3$ $[M + H]^+$ 327.1955, found 327.1953; LRMS (EI, m/z) 326 (M^+, 34), 270 (100), 255 (31), 165 (19), 57 (26); IR (film) 1057, 1233, 1710, 2901, 2972 cm^{-1}.

*1-(5-(Cyclopentylidene-p-tolylmethyl)-2-methylfuran-3-yl)ethan-1-one (**3k**):* yield 80% (47 mg); Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.17 (d, J = 7.8 Hz, 2H), 7.09 (d, J = 8.0 Hz, 2H), 5.98 (s, 1H), 2.77 (t, J = 7.2 Hz, 2H), 2.58 (s, 3H), 2.38 (s, 3H), 2.30 (s, 3H), 2.19 (t, J = 7.1 Hz, 2H), 1.83−1.76 (m, 2H),1.63−1.56 (m, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.4, 156.8, 154.0, 144.9, 137.6, 136.4, 129.3, 129.0, 122.6, 122.3, 107.9, 34.2, 33.0, 29.1, 27.1, 26.2, 21.2, 14.5; HRMS (ESI, m/z) calcd for $C_{20}H_{23}O_2$ $[M + H]^+$ 295.1693,

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found 295.1691; LRMS (EI, *m*/*z*) 294 (M^+, 100), 279 (92), 251 (26), 165 (30), 115 (22); IR (film) 798, 944, 1232, 1581, 1677 cm^{-1}.

Methyl 5-(cyclopentylidenep-tolylmethyl)-2-methylfuran-3-carboxylate (**3l**): yellow oil; yield 82% (51 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.16 (d, J = 7.9 Hz, 2H), 7.08 (d, J = 8.0 Hz, 2H), 6.04 (s, 1H), 3.75 (s, 3H), 2.75 (t, J = 7.2 Hz, 2H), 2.56 (s, 3H), 2.37 (s, 3H), 2.20 (t, J = 7.0 Hz, 2H), 1.82−1.75 (m, 2H), 1.63−1.56 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.7, 157.7, 154.1, 144.6, 137.5, 136.3, 129.3, 128.9, 122.7, 114.1, 108.2, 51.1, 34.1, 33.0, 27.1, 26.2, 21.2, 13.8; HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{23}O_3$ $[M + H]^+$ 311.1642, found 311.1639; LRMS (EI, *m*/*z*) 310 (M^+, 99), 295 (100), 235 (27), 165 (30), 115 (25); IR (film) 776, 1087, 1233, 1439, 1719 cm^{-1}.

1-(2-Methyl-5-(1-p-tolylvinyl)furan-3-yl)ethan-1-one (**3m**):[7] yellow oil; yield 75% (36 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.33 (d, J = 8.0 Hz, 2H), 7.20 (d, J = 7.9 Hz, 2H), 6.37 (s, 1H), 5.71 (s, 1H), 5.22 (s, 1H), 2.64 (s, 3H), 2.39 (s, 3H), 2.34 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 194.1, 158.5, 151.8, 138.3, 138.1, 136.1, 129.0, 128.1, 122.8, 112.1, 109.1, 29.1, 21.2, 14.5; LRMS (EI, *m*/*z*) 240 (M^+, 100), 225 (65), 182 (26), 153 (26), 115 (34).

(E)-2-Methyl-5-(1-p-tolylhex-1-en-1-yl)-3-tosylfuran (**3n**): colorless oil; yield 75% (61 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, J = 5.6 Hz, 2H), 7.26 (d, J = 8.0 Hz, 2H), 7.17 (d, J = 7.8 Hz, 2H), 7.05 (d, J = 8.0 Hz, 2H), 6.24 (t, J = 7.2 Hz, 1H), 5.91 (s, 1H), 2.59 (s, 3H), 2.38 (d, J = 1.7 Hz, 6H), 2.01 (q, J = 5.5 Hz, 2H), 1.40−1.33 (m, 2H), 1.28−1.22(m, 2H), 0.82 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 155.1, 154.3, 143.8, 139.7, 137.3, 133.3, 130.4, 129.7, 129.4, 129.0, 129.0, 126.8, 124.2, 106.1, 31.8, 28.5, 22.2, 21.5, 21.2, 13.8, 13.0; HRMS (ESI, *m*/*z*) calcd for $C_{25}H_{29}O_3S$ $[M + H]^+$ 409.1832, found 409.1834; LRMS (EI, *m*/*z*) 408 (M^+, 88), 393 (54), 365 (91), 165 (63), 91 (100); IR (film) 675, 709, 813, 1153, 1318 cm^{-1}.

(E)-2-Methyl-5-(3-phenyl-1-p-tolylprop-1-en-1-yl)furan (**3o**): yellow oil; yield 56% (32 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.29−7.17 (m, 9H), 6.36 (t, J = 7.8 Hz, 1H), 5.88 (d, J = 2.1 Hz, 1H), 5.67 (d, J = 2.9 Hz, 1H), 3.38 (d, J = 7.8 Hz, 2H), 2.38 (s, 3H), 2.29 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 153.9, 151.7, 141.1, 137.0, 134.3, 132.5, 129.6, 128.9, 128.4, 128.4, 125.9, 123.2, 109.1, 107.2, 35.0, 21.2, 13.7; HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{21}O$ $[M + H]^+$ 289.1587, found 289.1586; LRMS (EI, *m*/*z*) 288 (M^+, 68), 273 (100), 215 (33), 152 (34), 115 (40); IR (film) 698, 726, 782, 820, 1021 cm^{-1}.

Ethyl (E)-2-methyl-5-(1-phenylhex-1-en-1-yl)furan-3-carboxylate (**4a**): colorless oil; yield 87% (54 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.40−7.34 (m, 3H), 7.24 (t, J = 7.6 Hz, 2H), 6.27 (t, J = 7.7 Hz, 1H), 5.94 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.03 (q, J = 7.4 Hz, 2H), 1.41−1.26 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.1, 158.4, 153.3, 137.1, 131.1, 129.7, 128.2, 127.7, 127.4, 114.9, 107.6, 60.0, 32.0, 28.5, 22.3, 14.3, 13.9, 13.9; HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{25}O_3$ $[M + H]^+$ 313.1798, found 313.1792; LRMS (EI, *m*/*z*) 312 (M^+, 95), 269 (69), 256 (25), 223 (100), 181 (43); IR (film) 702, 776, 1084, 1231, 1716 cm^{-1}.

Ethyl (E)-5-(1-(4-methoxyphenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4b**): colorless oil; yield 72% (49 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.15 (d, J = 8.6 Hz, 2H), 6.92 (d, J = 8.7 Hz, 2H), 6.24 (t, J = 7.7 Hz, 1H), 5.96 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 3.84 (s, 3H), 2.60 (s, 3H), 2.04 (q, J = 7.5 Hz, 2H), 1.41−1.27 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.2, 158.9, 158.3, 153.6, 130.8, 130.6, 129.3, 127.6, 114.9, 113.6, 107.5, 60.0, 55.2, 32.0, 28.5, 22.3, 14.3, 13.9, 13.9; HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{27}O_4$ $[M + H]^+$ 343.1904, found 343.1896; LRMS (EI, *m*/*z*) 342 (M^+, 76), 311 (24), 299 (100), 253 (57), 211 (28); IR (film) 776, 1084, 1247, 1512, 1715 cm^{-1}.

Ethyl (E)-5-(1-(4-(methoxycarbonyl)phenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4c**): pale yellow oil; yield 80% (59 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 8.07 (d, J = 8.2 Hz, 2H), 7.32 (d, J = 8.2 Hz, 2H), 6.30 (t, J = 7.8 Hz, 1H), 5.92 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 3.94 (s, 3H), 2.61 (s, 3H), 2.01 (q, J = 7.5 Hz, 2H), 1.43−1.36 (m, 4H), 1.28 (t, J = 7.1 Hz, 3H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 166.9, 164.0, 158.6, 152.5, 142.0, 130.3, 129.8, 129.6, 129.3, 128.3, 115.0, 107.7, 60.0, 52.1, 31.8, 28.5, 22.2, 14.3, 13.8, 13.8; HRMS (ESI, *m*/*z*) calcd for $C_{22}H_{27}O_5$ $[M + H]^+$ 371.1853, found 371.1845; LRMS (EI, *m*/*z*) 370 (M^+, 100), 327 (44), 311 (59), 281 (57), 239 (35); IR (film) 776, 1084, 1232, 1276, 1721 cm^{-1}.

Ethyl (E)-5-(1-(4-acetylphenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4d**): yellow oil; yield 69% (49 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.99 (d, J = 8.3 Hz, 2H), 7.34 (d, J = 8.2 Hz, 2H), 6.31 (t, J = 7.8 Hz, 1H), 5.93 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.65 (s, 3H), 2.61 (s, 3H), 2.01 (q, J = 7.5 Hz, 2H), 1.43−1.27 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 197.8, 164.0, 158.6, 152.4, 142.2, 136.3, 130.3, 130.0, 128.4, 128.4, 115.0, 107.7, 60.1, 31.8, 28.6, 26.6, 22.3, 14.3, 13.9; HRMS (ESI, *m*/*z*) calcd for $C_{22}H_{27}O_4$ $[M + H]^+$ 355.1904, found 355.1899; LRMS (EI, *m*/*z*) 354 (M^+, 100), 311 (37), 298 (20), 269 (50), 223 (47); IR (film) 1084, 1232, 1263, 1686, 1716 cm^{-1}.

Ethyl (E)-5-(1-(4-chlorophenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4e**): pale yellow oil; yield 84% (58 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 8.4 Hz, 2H), 7.16 (d, J = 8.4 Hz, 2H), 6.27 (t, J = 7.7 Hz, 1H), 5.93 (s, 1H), 4.23 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.01 (q, J = 7.4 Hz, 2H), 1.41−1.27 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.0, 158.5, 152.8, 135.5, 133.4, 131.1, 130.0, 128.5, 128.2, 115.0, 107.6, 601, 31.9, 28.5, 22.3, 14.3, 13.9, 13.8; HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{24}ClO_3$ $[M + H]^+$ 347.1408, found 347.1401; LRMS (EI, *m*/*z*) 346 (M^+, 79), 303 (76), 290 (26), 257 (100), 215 (42); IR (film) 776, 1084, 1232, 1492, 1716 cm^{-1}.

Ethyl (E)-5-(1-(4-bromophenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4f**): pale yellow oil; yield 81% (63 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.52 (d, J = 8.3 Hz, 2H), 7.11 (d, J = 8.3 Hz, 2H), 6.27 (t, J = 7.7 Hz, 1H), 5.93 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.00 (q, J = 7.4 Hz, 2H), 1.43−1.27 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.0, 158.6, 152.7, 136.0, 131.5, 131.4, 130.0, 128.2, 121.5, 115.0, 107.6, 60.1, 31.9, 28.5, 22.3, 14.3, 13.9, 13.8; HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{24}{}^{79}BrO_3$ $[M + H]^+$ 391.0903, found 391.0902; LRMS (EI, *m*/*z*) 392 (M^+ for ^{81}Br, 33), 390 (M^+ for ^{79}Br, 32), 347 (19), 311 (23), 268 (100), 239 (23); IR (film) 776, 1083, 1231, 1716, 2969 cm^{-1}.

Ethyl (E)-5-(1-(3-methoxyphenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4g**): pale yellow oil; yield 90% (62 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.30 (t, J = 7.8 Hz, 1H), 6.90−6.77 (m, 3H), 6.25 (t, J = 7.7 Hz, 1H), 5.98 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 3.81 (s, 3H), 2.60 (s, 3H), 2.04 (q, J = 7.4 Hz, 2H), 1.43−1.27(m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.1, 159.4, 158.4, 153.1, 138.5, 131.0, 129.2, 127.7, 122.1, 115.3, 114.9, 112.9, 107.6, 60.0, 55.2, 32.0, 28.5, 22.3, 14.3, 13.9, 13.9; HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{27}O_4$ $[M + H]^+$ 343.1904, found 343.1896; LRMS (EI, *m*/*z*) 342 (M^+, 100), 311 (23), 299 (85), 253 (48), 211 (29); IR (film) 708, 776, 1084, 1229, 1716 cm^{-1}.

Ethyl (E)-5-(1-(3-bromophenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4h**): pale yellow oil; yield 70% (55 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.50−7.47 (m, 1H), 7.38 (t, J = 1.6 Hz, 1H), 7.26 (t, J = 7.8 Hz, 1H), 7.17−7.15 (m, 1H), 6.27 (t, J = 7.7 Hz, 1H), 5.94 (s, 1H), 4.23 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.01 (q, J = 7.4 Hz, 2H), 1.43−1.26 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.0, 158.6, 152.6, 139.2, 132.6, 130.6, 129.9, 129.8, 128.5, 128.4, 122.3, 115.0, 107.7, 60.1, 31.8, 28.5, 22.3, 14.3, 13.9; HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{24}{}^{79}BrO_3$ $[M + H]^+$ 391.0903, found 391.0899; LRMS (EI, *m*/*z*) 392 (M^+ for ^{81}Br, 34), 390 (M^+ for ^{79}Br, 33), 347 (16), 311 (23), 268 (100), 239 (20); IR (film) 704, 776, 1083, 1231, 1716 cm^{-1}.

Ethyl (E)-2-methyl-5-(1-(m-tolyl)hex-1-en-1-yl)furan-3-carboxylate (**4i**): colorless oil; yield 97% (63 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.27 (t, J = 7.5 Hz, 1H), 7.15 (d, J = 7.5 Hz, 1H), 7.03−7.01 (m, 2H), 6.25 (t, J = 7.7 Hz, 1H), 5.95 (s, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.37 (s, 3H), 2.03 (q, J = 7.4 Hz, 2H), 1.43−1.26 (m, 7H), 0.84 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 164.2, 158.3, 153.4, 137.8, 137.0, 131.2, 130.3, 128.1, 128.1, 127.6, 126.7, 114.9, 107.5, 60.0, 32.0, 28.5, 22.3, 21.44, 14.3, 13.9, 13.9; HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{27}O_3$ $[M + H]^+$ 327.1955, found 327.1952; LRMS (EI, *m*/*z*) 326 (M^+, 97), 283 (84), 237 (100), 195 (53), 165 (39); IR (film) 776, 1082, 1232, 1716, 2970 cm^{-1}.

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*Ethyl (E)-5-(1-(2-methoxyphenyl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4j**):* colorless oil; yield 88% (60 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35−7.31 (m, 1H), 7.11 (dd, J = 1.7, 7.4 Hz, 1H), 7.00−6.94 (m, 2H), 6.34 (t, J = 7.6 Hz, 1H), 5.88 (s, 1H), 4.21 (q, J = 7.1 Hz, 2H), 3.76 (s, 3H), 2.59 (s, 3H), 1.93 (q, J = 7.3 Hz, 2H), 1.42−1.26 (m, 7H), 0.82 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.2, 158.2, 157.2, 152.9, 131.4, 129.0, 128.4, 127.2, 125.7, 120.5, 114.9, 111.0, 106.8, 60.0, 55.6, 31.5, 28.8, 22.3, 14.3, 13.9; HRMS (ESI, m/z) calcd for $C_{21}H_{27}O_4$ $[M + H]^+$ 343.1904, found 343.1896; LRMS (EI, m/z) 342 (M^+, 100), 299 (87), 271 (59), 253 (52), 211 (32); IR (film) 754, 776, 1084, 1231, 1715 cm^{-1}.

*Ethyl (E)-2-methyl-5-(1-(o-tolyl)hex-1-en-1-yl)furan-3-carboxylate (**4k**):* colorless oil; yield 94% (61 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26−7.16 (m, 3H), 7.07 (d, J = 7.2 Hz, 1H), 6.30 (t, J = 7.6 Hz, 1H), 5.78 (s, 1H), 4.21 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.15 (s, 3H), 1.91−1.84 (m, 2H), 1.40−1.26 (m, 7H), 0.82 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.2, 158.4, 152.7, 136.7, 136.5, 130.2, 130.0, 130.0, 127.6, 125.7, 115.0, 107.2, 60.0, 31.6, 28.5, 22.3, 19.3, 14.3, 13.9; HRMS (ESI, m/z) calcd for $C_{21}H_{27}O_3$ $[M + H]^+$ 327.1955, found 327.1954; LRMS (EI, m/z) 326 (M^+, 100), 283 (73), 237 (72), 195 (34), 165 (31); IR (film) 731, 776, 1084, 1231, 1717 cm^{-1}.

*Ethyl (E)-2-methyl-5-(1-(naphthalen-1-yl)hex-1-en-1-yl)furan-3-carboxylate (**4l**):* colorless oil; yield 88% (64 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81−7.72 (m, 3H), 7.44−7.30 (m, 3H), 7.25 (d, J = 7.0 Hz, 1H), 6.46 (t, J = 7.6 Hz, 1H), 5.62 (s, 1H), 4.10−4.04 (m, 2H), 2.55 (s, 3H), 1.78−1.72 (m, 2H), 1.30−1.09 (m, 7H), 0.67 (t, J = 7.3 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.1, 158.4, 153.1, 134.7, 133.7, 132.0, 129.3, 129.0, 128.2, 128.0, 127.5, 126.1, 125.8, 125.6, 125.4, 115.0, 107.6, 60.0, 31.6, 28.8, 22.3, 14.3, 13.9, 13.9; HRMS (ESI, m/z) calcd for $C_{24}H_{27}O_3$ $[M + H]^+$ 363.1955, found 363.1953; LRMS (EI, m/z) 362 (M^+, 100), 305 (68), 202 (43), 189 (31), 165 (49); IR (film) 776, 797, 1086, 1232, 1716 cm^{-1}.

*Ethyl (E)-2-methyl-5-(1-(naphthalen-2-yl)hex-1-en-1-yl)furan-3-carboxylate (**4m**):* colorless oil; yield 88% (64 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88−7.83 (m, 3H), 7.71 (s, 1H), 7.51−7.48 (m, 2H), 7.35 (dd, J = 1.5, 8.3 Hz, 1H), 6.35 (t, J = 7.7 Hz, 1H), 5.95 (s, 1H), 4.19 (q, J = 7.1 Hz, 2H), 2.62 (s, 3H), 2.07 (q, J = 7.5 Hz, 2H), 1.45−1.22 (m, 7H), 0.82 (t, J = 7.3 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.1, 158.5, 153.3, 134.7, 133.3, 132.7, 131.0, 128.6, 128.2, 128.0, 127.9, 127.9, 127.7, 126.1, 126.0, 115.0, 107.8, 60.0, 32.0, 28.6, 22.3, 14.3, 13.9, 13.9; HRMS (ESI, m/z) calcd for $C_{24}H_{27}O_3$ $[M + H]^+$ 363.1955, found 363.1947; LRMS (EI, m/z) 362 (M^+, 99), 319 (100), 273 (53), 231 (28), 165 (30); IR (film) 733, 908, 1085, 1231, 1714 cm^{-1}.

*Ethyl (E)-2-methyl-5-(1-(thiophen-3-yl)hex-1-en-1-yl)furan-3-carboxylate (**4n**):* pale yellow oil; yield 65% (41 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35−7.32 (m, 1H), 7.18 (dd, J = 1.0 Hz, 2.9 Hz, 1H), 7.02 (dd, J = 1.0 Hz, 4.9 Hz, 1H), 6.27 (t, J = 7.7 Hz, 1H), 6.09 (s, 1H), 4.24 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.13 (q, J = 7.4 Hz, 2H), 1.43−1.25 (m, 7H), 0.86 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.1, 158.3, 152.9, 136.8, 129.1, 128.8, 125.9, 124.9, 124.1, 114.9, 107.4, 60.0, 32.0, 28.7, 22.4, 14.4, 13.9, 13.9; HRMS (ESI, m/z) calcd for $C_{18}H_{23}O_3S$ $[M + H]^+$ 319.1362, found 319.1356; LRMS (EI, m/z) 318 (M^+, 100), 275 (96), 262 (27), 229 (94), 187 (47); IR (film) 776, 848, 1084, 1231, 1715 cm^{-1}.

*Ethyl (E)-5-(1-(furan-3-yl)hex-1-en-1-yl)-2-methylfuran-3-carboxylate (**4o**):* yellow oil; yield 63% (38 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47 (t, J = 1.6 Hz, 1H), 7.43 (s, 1H), 6.41 (d, J = 1.5 Hz, 1H), 6.27−6.23 (m, 2H), 4.25 (q, J = 7.1 Hz, 2H), 2.60 (s, 3H), 2.20 (q, J = 7.4 Hz, 2H), 1.44−1.30 (m, 7H), 0.88 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.1, 158.3, 152.7, 142.5, 141.3, 129.1, 121.7, 120.3, 114.9, 112.0, 107.2, 60.0, 32.0, 28.7, 22.4, 14.3, 13.9, 13.8; HRMS (ESI, m/z) calcd for $C_{18}H_{23}O_4$ $[M + H]^+$ 303.1591, found 303.1582; LRMS (EI, m/z) 302 (M^+, 97), 259 (63), 213 (100), 185 (23), 171 (37); IR (film) 777, 874, 1085, 1232, 1715 cm^{-1}.

*tert-Butyl 2-methyl-5-((1E,3E)-1-phenylocta-1,3-dien-3-yl)furan-3-carboxylate (**6a**):* colorless oil; yield 89% (65 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46−7.44 (m, 2H), 7.34 (t, J = 7.5 Hz, 2H), 7.27−7.25 (m, 1H), 7.00 (d, J = 16.3 Hz, 1H), 6.79 (d, J = 16.3 Hz, 1H), 6.51 (s, 1H), 6.04 (t, J = 7.7 Hz, 1H), 2.58 (s, 3H), 2.37 (q, J = 7.4 Hz, 2H), 1.55 (s, 9H), 1.51−1.47 (m, 2H), 1.42−1.38 (m, 2H), 0.93 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 163.6, 157.4, 151.7, 137.5, 132.5, 132.1, 128.6, 128.0, 127.7, 126.5, 123.0, 116.1, 107.6, 80.5, 31.7, 28.3, 28.1, 22.4, 14.0, 13.9; HRMS (ESI, m/z) calcd for $C_{24}H_{31}O_3$ $[M + H]^+$ 367.2268, found 367.2268; LRMS (EI, m/z) 366 (M^+, 40), 267 (100), 253 (36), 207 (56), 165 (68); IR (film) 693, 778, 1092, 1171, 1709 cm^{-1}.

*Ethyl 2-methyl-5-((1E,3E)-1-phenylocta-1,3-dien-3-yl)furan-3-carboxylate (**6b**):* yellow oil; yield 87% (59 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (d, J = 7.2 Hz, 2H), 7.34 (t, J = 7.5 Hz, 2H), 7.27−7.25 (m, 1H), 6.99 (d, J = 16.3 Hz, 1H), 6.79 (d, J = 16.3 Hz, 1H), 6.56 (s, 1H), 6.06 (t, J = 7.7 Hz, 1H), 4.29 (q, J = 7.1 Hz, 2H), 2.61 (s, 3H), 2.37 (q, J = 7.4 Hz, 2H), 1.51−1.33 (m, 7H), 0.93 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.2, 158.1, 151.9, 137.4, 132.6, 132.1, 128.6, 127.8, 127.7, 126.5, 122.9, 114.7, 107.3, 60.0, 31.7, 28.1, 22.4, 14.4, 13.9, 13.8; HRMS (ESI, m/z) calcd for $C_{22}H_{27}O_3$ $[M + H]^+$ 339.1955, found 339.1953; LRMS (EI, m/z) 338 (M^+, 57), 295 (100), 207 (40), 178 (40), 165 (56); IR (film) 693, 777, 1092, 1230, 1715 cm^{-1}.

*Methyl 5-((1E,3E)-1,5-diphenylpenta-1,3-dien-3-yl)-2-methylfuran-3-carboxylate (**6c**):* colorless oil; yield 84% (60 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47 (d, J = 7.2 Hz, 1H), 7.37−7.20 (m, 9H), 7.07 (d, J = 16.3 Hz, 1H), 6.88 (d, J = 16.3 Hz, 1H), 6.60 (s, 1H), 6.24 (t, J = 7.8 Hz, 1H), 3.81 (s, 3H), 3.72 (d, J = 7.8 Hz, 2H), 2.59 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.5, 158.5, 151.6, 140.1, 137.1, 133.8, 128.9, 128.7, 128.6, 128.6, 128.5, 128.0, 126.6, 126.2, 122.4, 114.5, 107.8, 51.3, 34.6, 13.8; HRMS (ESI, m/z) calcd for $C_{24}H_{23}O_3$ $[M + H]^+$ 359.1642, found 359.1642; LRMS (EI, m/z) 358 (M^+, 100), 280 (52), 267 (57), 165 (71), 91 (59); IR (film) 695, 751, 1084, 1232, 1716 cm^{-1}.

*1-(5-((1E,3E)-1,5-Diphenylpenta-1,3-dien-3-yl)-2-methylfuran-3-yl)ethan-1-one (**6d**):* dark yellow oil; yield 93% (64 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 (d, J = 7.4 Hz, 1H), 7.38−7.21 (m, 9H), 7.08 (d, J = 16.3 Hz, 1H), 6.87 (d, J = 16.3 Hz, 1H), 6.56 (s, 1H), 6.24 (t, J = 7.8 Hz, 1H), 3.73 (d, J = 7.8 Hz, 2H), 2.60 (s, 3H), 2.40 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.1, 157.7, 151.6, 140.1, 137.0, 133.9, 129.2, 128.7, 128.6, 128.5, 128.4, 128.0, 126.6, 126.3, 122.7, 122.5, 107.5, 34.7, 29.1, 14.4; HRMS (ESI, m/z) calcd for $C_{24}H_{23}O_2$ $[M + H]^+$ 343.1693, found 343.1692; LRMS (EI, m/z) 342 (M^+, 96), 283 (66), 207 (100), 165 (74), 77 (59); IR (film) 695, 750, 952, 1231, 1676 cm^{-1}.

*Methyl 5-((1E,3E)-5-(Benzyloxy)-1-phenylpenta-1,3-dien-3-yl)-2-methylfuran-3-carboxylate (**6e**):* pale yellow oil; yield 77% (60 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42−7.27 (m, 9H), 6.82 (AB quart, J = 16.5 Hz, 2H), 6.63 (s, 1H), 6.26 (t, J = 6.8 Hz, 1H), 4.58 (s, 2H), 4.35 (d, J = 6.8 Hz, 2H), 3.81 (s, 3H), 2.61 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.3, 158.9, 151.0, 138.1, 136.8, 134.6, 130.4, 128.6, 128.4, 128.1, 127.8, 127.6, 126.6, 125.2, 122.0, 114.6, 108.4, 72.4, 66.4, 51.2, 13.8; HRMS (ESI, m/z) calcd for $C_{25}H_{25}O_4$ $[M + H]^+$ 389.1747, found 389.1748; IR (film) 695, 733, 1091, 1232, 1717 cm^{-1}.

*1-(5-((1E,3E)-5-(Benzyloxy)-1-phenylpenta-1,3-dien-3-yl)-2-methylfuran-3-yl)ethan-1-one (**6f**):* yellow oil; yield 75% (56 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.41 (m, 2H), 7.38−7.28 (m, 8H), 6.82 (AB quart, J = 16.3 Hz, 2H), 6.59 (s, 1H), 6.27 (t, J = 6.8 Hz, 1H), 4.58 (s, 2H), 4.36 (d, J = 6.8 Hz, 2H), 2.62 (s, 3H), 2.39 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.0, 158.0, 151.0, 138.1, 136.7, 134.8, 130.3, 128.6, 128.4, 128.2, 127.8, 127.6, 126.6, 125.4, 122.7, 122.0, 108.1, 72.4, 66.4, 29.0, 14.4; HRMS (ESI, m/z) calcd for $C_{25}H_{25}O_3$ $[M + H]^+$ 373.1798, found 373.1798; IR (film) 695, 749, 951, 1072, 1676 cm^{-1}.

*Ethyl (E)-2-methyl-5-(4-methyl-1-phenylpenta-1,3-dien-3-yl)-furan-3-carboxylate (**6g**):* colorless oil; yield 81% (50 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 7.4 Hz, 2H), 7.29 (t, J = 7.6 Hz, 2H), 7.19 (t, J = 7.8 Hz, 2H), 6.48 (s, 1H), 6.21 (d, J = 15.9 Hz, 1H), 4.31 (q, J = 7.1 Hz, 2H), 2.61 (s, 3H), 2.04 (s, 3H), 1.82 (s, 3H), 1.37 (t, J = 7.1 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.4, 158.1, 150.0, 139.9, 137.8, 130.1, 128.5, 127.2, 126.3, 125.0, 114.2, 110.1, 60.1, 23.6, 20.7, 14.4, 13.9; HRMS (ESI, m/z) calcd for

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$C_{20}H_{23}O_3$ [M + H]$^+$ 311.1642, found 311.1643; LRMS (EI, m/z) 310 (M$^+$, 100), 295 (45), 221 (45), 179 (32), 115 (25); IR (film) 753, 1043, 1092, 1228, 1714 cm^{-1}.

*tert-Butyl (E)-2-methyl-5-(4-methyl-1-phenylpenta-1,3-dien-3-yl)furan-3-carboxylate (**6h**):* yellow oil; yield 73% (49 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (d, J = 8.0 Hz, 2H), 7.21 (t, J = 7.5 Hz, 2H), 7.14−7.09 (m, 2H), 6.35 (s, 1H), 6.14 (d, J = 15.9 Hz, 1H), 2.60 (s, 3H), 1.96 (s, 3H), 1.74 (s, 3H), 1.50 (s, 9H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 163.8, 157.3, 149.6, 139.8, 137.9, 130.0, 128.5, 127.2, 126.4, 126.3, 125.1, 115.6, 110.4, 80.4, 28.3, 23.6, 20.7, 13.9; HRMS (ESI, m/z) calcd for $C_{22}H_{27}O_3$ [M + H]$^+$ 339.1955, found 339.1955; LRMS (EI, m/z) 338 (M$^+$, 79), 267 (100), 221 (60), 178 (43), 57 (71); IR (film) 753, 1092, 1171, 1231, 1709 cm^{-1}.

*(E)-1-(5-(1-Cyclopentylidene-3-phenylallyl)-2-methylfuran-3-yl)-ethan-1-one (**6i**):* dark yellow oil; yield 73% (45 mg); ^{13}C{^{1}H} NMR (400 MHz, $CDCl_3$) δ 7.39 (d, J = 7.4 Hz, 2H), 7.31 (t, J = 7.6 Hz, 2H), 7.23−7.19 (m, 1H),7.02 (d, J = 16.0 Hz, 1H), 6.48 (s, 1H), 6.42 (d, J = 16.1 Hz, 1H), 2.62−2.60 (m, 5H), 2.47−2.43 (m, 5H), 1.81−1.76 (m, 2H), 1.74−1.68 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.3, 157.1, 151.6, 150.6, 137.9, 129.3, 128.6, 127.3, 127.0, 126.3, 122.3, 121.1, 109.1, 33.8, 31.8, 29.2, 26.5, 26.3, 14.5; HRMS (ESI, m/z) calcd for $C_{21}H_{23}O_2$ [M + H]$^+$ 307.1693, found 307.1698; LRMS (EI, m/z) 306 (M$^+$, 100), 263 (34), 165 (26), 115 (28), 91 (39); IR (film) 693, 752, 953, 1229, 1676 cm^{-1}.

*2-Methyl-5-((1E,3E)-1-phenylocta-1,3-dien-3-yl)-3-tosylfuran (**6j**):* yellow oil; yield 77% (65 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, J = 7.4 Hz, 2H), 7.42 (d, J = 7.9 Hz, 2H), 7.36−7.25 (m, 5H), 6.91 (d, J = 16.3 Hz, 1H), 6.71 (d, J = 16.3 Hz, 1H), 6.46 (s, 1H), 6.03 (t, J = 7.7 Hz, 1H), 2.60 (s, 3H), 2.41 (s, 3H), 2.34 (q, J = 7.4 Hz, 2H), 1.47−1.34 (m, 4H), 0.91 (t, J = 7.5 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 155.0, 153.0, 144.0, 139.7, 137.1, 133.2, 133.0, 129.9, 128.7, 128.0, 127.3, 127.0, 126.5, 124.1, 122.4, 106.0, 31.6, 28.2, 22.4, 21.6, 13.9, 13.0; HRMS (ESI, m/z) calcd for $C_{26}H_{29}O_3S$ [M + H]$^+$ 421.1832, found 421.1822; LRMS (EI, m/z) 420 (M$^+$, 37), 377 (35), 207 (100), 178 (23), 91 (72); IR (film) 678, 755, 1157, 1302, 1317 cm^{-1}.

*tert-Butyl 2-methyl-5-((1E,3E)-1-p-tolylocta-1,3-dien-3-yl)furan-3-carboxylate (**6k**):* yellow oil; yield 97% (74 mg); ^{13}C{^{1}H} NMR (400 MHz, $CDCl_3$) δ 7.35 (d, J = 8.1 Hz, 2H), 7.15 (d, J = 8.0 Hz, 2H), 6.94 (d, J = 16.3 Hz, 1H), 6.76 (d, J = 16.3 Hz, 1H), 6.50 (s, 1H), 6.01 (t, J = 7.7 Hz, 1H), 2.57 (s, 3H), 2.39−2.32 (m, 5H), 1.55 (s, 9H), 1.48−1.37 (m, 4H), 0.93 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.6, 157.3, 151.8, 137.6, 134.7, 132.4, 131.7, 129.3, 128.1, 126.4, 122.0, 116.1, 107.6, 80.4, 31.8, 28.3, 28.1, 22.4, 21.2, 14.0, 13.9; HRMS (ESI, m/z) calcd for $C_{25}H_{33}O_3$ [M + H]$^+$ 381.2424, found 381.2428; LRMS (EI, m/z) 380 (M$^+$, 57), 281 (99), 267 (100), 219 (59), 105 (59); IR (film) 778, 1091, 1172, 1234, 1710 cm^{-1}.

*tert-Butyl 5-((1E,3E)-1-(4-chlorophenyl)octa-1,3-dien-3-yl)-2-methylfuran-3-carboxylate (**6l**):* yellow oil; yield 80% (64 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 8.6 Hz, 2H), 7.30 (d, J = 8.6 Hz, 2H), 6.97 (d, J = 16.3 Hz, 1H), 6.73 (d, J = 16.3 Hz, 1H), 6.50 (s, 1H), 6.05 (t, J = 7.7 Hz, 1H), 2.58 (s, 3H), 2.36 (q, J = 7.4 Hz, 2H), 1.56 (s, 9H), 1.51−1.47 (m, 2H), 1.42−1.38 (m, 2H), 0.93 (t, J = 7.2 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 163.6, 157.4, 151.5, 136.0, 133.3, 132.8, 131.1, 128.8, 127.8, 127.6, 123.6, 116.1, 107.7, 80.5, 31.7, 28.3, 28.1, 22.4, 13.9, 13.9; HRMS (ESI, m/z) calcd for $C_{24}H_{30}ClO_3$ [M + H]$^+$ 401.1878, found 401.1867; LRMS (EI, m/z) 400 (M$^+$, 17), 301 (44), 207 (100), 91 (41), 73 (52); IR (film) 778, 1091, 1171, 1234, 1709 cm^{-1}.

*tert-Butyl 2-methyl-5-((4E,6E)-undeca-4,6-dien-6-yl)furan-3-carboxylate (**6m**):* pale yellow oil; yield 95% (63 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.40 (s, 1H), 6.19 (d, J = 15.9 Hz, 1H), 5.92−5.84 (m, 2H), 2.54 (s, 3H), 2.25 (q, J = 7.3 Hz, 2H), 2.18−2.12 (m, 2H), 1.55 (s, 9H), 1.49−1.33 (m, 6H), 0.96−0.90 (m, 6H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 163.7, 157.1, 152.3, 135.2, 129.1, 127.9, 123.9, 116.0, 107.1, 80.3, 35.4, 31.8, 28.3, 27.9, 22.4, 22.4, 13.9, 13.7; HRMS (ESI, m/z) calcd for $C_{21}H_{33}O_3$ [M + H]$^+$ 333.2424, found 333.2417; LRMS (EI, m/z) 332 (M$^+$, 20), 259 (14), 233 (100), 191 (11), 57 (21); IR (film) 778, 1090, 1174, 1234, 1712 cm^{-1}.

*Methyl 2-methyl-5-((4E,6E)-undeca-4,6-dien-6-yl)furan-3-carboxylate (**6n**):* yellow oil; yield 86% (50 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.40 (s, 1H), 6.20 (d, J = 15.9 Hz, 1H), 5.95−5.84 (m, 2H), 3.82 (s, 3H), 2.59 (s, 3H), 2.39 (s, 3H), 2.27 (q, J = 7.3 Hz, 2H), 2.20−2.14 (m, 2H), 1.51−1.34 (m, 6H), 0.97−0.90 (m, 6H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 194.2, 157.2, 152.6, 135.4, 129.6, 127.7, 123.8, 122.6, 106.4, 35.3, 31.7, 29.0, 28.0, 22.4, 22.4, 14.4, 13.9, 13.6; HRMS (ESI, m/z) calcd for $C_{18}H_{27}O_3$ [M + H]$^+$ 291.1955, found 291.1954; LRMS (EI, m/z) 290 (M$^+$, 54), 245 (100), 128 (26), 115 (29), 91 (26); IR (film) 777, 1074, 1103, 1230, 1720 cm^{-1}.

*Methyl (E)-5-(1-cyclopentylidenehex-2-en-1-yl)-2-methylfuran-3-carboxylate (**6o**):* yellow oil; yield 75% (43 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.41 (s, 1H), 6.22 (d, J = 15.7 Hz, 1H), 5.60−5.53 (m, 1H), 3.82 (s, 3H), 2.58 (s, 3H), 2.49−2.38 (m, 4H), 2.10 (q, J = 7.1 Hz, 2H), 1.74−1.63 (m, 4H), 1.46−1.36 (m, 2H), 0.91 (t, J = 7.3 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 164.8, 157.5, 151.4, 147.6, 131.8, 127.7, 120.6, 113.8, 108.7, 51.2, 35.2, 33.3, 31.7, 26.5, 26.2, 22.6, 13.8, 13.7; HRMS (ESI, m/z) calcd for $C_{18}H_{25}O_3$ [M + H]$^+$ 289.1798, found 289.1804; LRMS (EI, m/z) 288 (M$^+$, 38), 231 (100), 189 (23), 136 (14), 115 (16); IR (film) 950, 1230, 1398, 1583, 1679 cm^{-1}.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b01350.

Optimization study, E/Z ratio analysis, and copies of ^{1}H and ^{13}C NMR spectra for all new products (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For reviews, see: (a) Zhang, Y.; Wang, J. *Eur. J. Org. Chem.* **2011**, *2011*, 1015. (b) Barluenga, J.; Valdés, C. *Angew. Chem., Int. Ed.* **2011**, *50*, 7486. (c) Shao, Z.; Zhang, H. *Chem. Soc. Rev.* **2012**, *41*, 560. (d) Xiao, Q.; Zhang, Y.; Wang, J. *Acc. Chem. Res.* **2013**, *46*, 236. (e) Xia, Y.; Zhang, Y.; Wang, J. *ACS Catal.* **2013**, *3*, 2586.

(2) For recent examples, see: (a) Kitamura, M.; Yuasa, R.; Van Vranken, D. L. *Tetrahedron Lett.* **2015**, *56*, 3027. (b) Zhou, P.-X.; Ye, Y.-Y.; Zhao, L.-B.; Hou, J.-Y.; Kang, X.; Chen, D.-Q.; Tang, Q.; Zhang, J.-Y.; Huang, Q.-X.; Zheng, L.; Ma, J.-W.; Xu, P.-F.; Liang, Y.-M. *Chem. - Eur. J.* **2014**, *20*, 16093. (c) Aziz, J.; Frison, G.; Gómez, M.; Brion, J.-D.; Hamze, A.; Alami, M. *ACS Catal.* **2014**, *4*, 4498. (d) Wang, P.-S.; Lin, H.-C.; Zhou, X.-L.; Gong, L.-Z. *Org. Lett.* **2014**, *16*, 3332. (e) Zhou, P.-X.; Ye, Y.-Y.; Ma, J.-W.; Zheng, L.; Tang, Q.; Qiu, Y.-F.; Song, B.; Qiu, Z.-H.; Xu, P.-F.; Liang, Y.-M. *J. Org. Chem.* **2014**, *79*, 6627. (f) Zhou, P.-X.; Zheng, L.; Ma, J.-W.; Ye, Y.-Y.; Liu, X.-Y.; Xu, P.-F.; Liang, Y.-M. *Chem. - Eur. J.* **2014**, *20*, 6745. (g) Barroso, R.; Valencia, R. A.; Cabal, M.-P.; Valdés, C. *Org. Lett.* **2014**, *16*, 2264. (h) Xia, Y.; Xia, Y.; Liu, Z.; Zhang, Y.; Wang, J. *J. Org. Chem.* **2014**, *79*, 7711.

(3) For reviews on oxidative couplings, see: (a) Yeung, C. S.; Dong, V. M. *Chem. Rev.* **2011**, *111*, 1215. (b) Liu, C.; Zhang, H.; Shi, W.; Lei, A. *Chem. Rev.* **2011**, *111*, 1780. (c) Shi, W.; Liu, C.; Lei, A. *Chem. Soc. Rev.* **2011**, *40*, 2761. (d) Li, B.-J.; Shi, Z.-J. *Chem. Soc. Rev.* **2012**, *41*, 5588.

DOI: 10.1021/acs.joc.5b01350
J. Org. Chem. 2015, 80, 7856−7864

(4) (a) Peng, C.; Wang, Y.; Wang, J. *J. Am. Chem. Soc.* **2008**, *130*, 1566. (b) Zhao, X.; Jing, J.; Lu, K.; Zhang, Y.; Wang, J. *Chem. Commun.* **2010**, *46*, 1724. (c) Tsoi, Y.-T.; Zhou, Z.; Chan, A. S. C.; Yu, W.-Y. *Org. Lett.* **2010**, *12*, 4506. (d) Xia, Y.; Xia, Y.; Liu, Z.; Zhang, Y.; Wang, J. *J. Org. Chem.* **2014**, *79*, 7711. (e) Zhou, L.; Ye, F.; Ma, J.; Zhang, Y.; Wang, J. *Angew. Chem., Int. Ed.* **2011**, *50*, 3510. (f) Chen, H.; Huang, L.; Fu, W.; Liu, X.; Jiang, H. *Chem. - Eur. J.* **2012**, *18*, 10497. (g) Zeng, X.; Cheng, G.; Shen, J.; Cui, X. *Org. Lett.* **2013**, *15*, 3022. (h) Roche, M.; Frison, G.; Brion, J.-D.; Provot, O.; Hamze, A.; Alami, M. *J. Org. Chem.* **2013**, *78*, 8485.

(5) For a review, see: Miki, K.; Uemura, S.; Ohe, K. *Chem. Lett.* **2005**, *34*, 1068.

(6) For selected examples, see: Cr(0)-catalyzed reactions: (a) Miki, K.; Nishino, F.; Ohe, K.; Uemura, S. *J. Am. Chem. Soc.* **2002**, *124*, 5260. (b) Miki, K.; Yokoi, T.; Nishino, F.; Kato, Y.; Washitake, Y.; Ohe, K.; Uemura, S. *J. Org. Chem.* **2004**, *69*, 1557. Rh(II)-catalyzed reactions: (c) Kato, Y.; Miki, K.; Nishino, F.; Ohe, K.; Uemura, S. *Org. Lett.* **2003**, *5*, 2619. (d) Miki, K.; Washitake, Y.; Ohe, K.; Uemura, S. *Angew. Chem., Int. Ed.* **2004**, *43*, 1857. (e) González, M. J.; López, E.; Vicente, R. *Chem. Commun.* **2014**, *50*, 5379. Zn(II)-catalyzed reactions: (f) Vicente, R.; González, J.; Riesgo, L.; González, J.; López, L. *Angew. Chem., Int. Ed.* **2012**, *51*, 8063. (g) González, J.; González, J.; Pérez-Calleja, C.; López, L.; Vicente, R. *Angew. Chem., Int. Ed.* **2013**, *52*, 5853. (h) Song, B.; Li, L.-H.; Song, X.-R.; Qiu, Y.-F.; Zhong, M.-J.; Zhou, P.-X.; Liang, Y.-M. *Chem. - Eur. J.* **2014**, *20*, 5910. (i) González, M. J.; López, L. A.; Vicente, R. *Org. Lett.* **2014**, *16*, 5780. Au-catalyzed reactions: (j) Wang, T.; Zhang, J. *Dalton Trans.* **2010**, *39*, 4270. (k) Ma, J.; Jiang, H.; Zhu, S. *Org. Lett.* **2014**, *16*, 4472. Cu(I)-catalyzed reaction: (l) Cao, H.; Zhan, H.; Cen, J.; Lin, J.; Lin, Y.; Zhu, Q.; Fu, M.; Jiang, H. *Org. Lett.* **2013**, *15*, 1080. Pd(II)-catalyzed reaction: (m) Zhan, H.; Lin, X.; Qiu, Y.; Du, Z.; Li, P.; Li, Y.; Cao, H. *Eur. J. Org. Chem.* **2013**, *2013*, 2284. Metal-free reactions: (n) Clark, J. S.; Boyer, A.; Aimon, A.; Engel García, P.; Lindsay, D. M.; Symington, A. D. F.; Danoy, Y. *Angew. Chem., Int. Ed.* **2012**, *51*, 12128. (o) Clark, J. S.; Romiti, F.; Hogg, K. F.; Hamid, M. H. S. A.; Richter, S. C.; Boyer, A.; Redman, J. C.; Farrugia, L. J. *Angew. Chem., Int. Ed.* **2015**, *54*, 5744.

(7) Xia, Y.; Qu, S.; Xiao, Q.; Wang, Z.-X.; Qu, P.; Chen, L.; Liu, Z.; Tian, L.; Huang, Z.; Zhang, Y.; Wang, J. *J. Am. Chem. Soc.* **2013**, *135*, 13502.

(8) For a related Cu(I)-catalyzed reaction, see: Hu, F.; Xia, Y.; Ma, C.; Zhang, Y.; Wang, J. *Org. Lett.* **2014**, *16*, 4082.

(9) (a) Hashmi, A. S. K.; Ruppert, T. L.; Knöfel, T.; Bats, J. W. *J. Org. Chem.* **1997**, *62*, 7295. (b) Hashmi, A. S. K.; Choi, J.-H.; Bats, J. W. *J. Prakt. Chem.* **1999**, *341*, 342. (c) Hashmi, A. S. K.; Schwarz, L.; Choi, J.-H.; Frost, T. M. *Angew. Chem., Int. Ed.* **2000**, *39*, 2285. (d) Hashmi, A. S. K.; Schwarz, L.; Bolte, M. 2004, 1923. (e) Sevov, C. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **2014**, *136*, 10625 and references cited therein.

(10) Recently, we have communicated the related Pd-catalyzed oxidative coupling with terminal alkynes; see: Xia, Y.; Liu, Z.; Ge, R.; Xiao, Q.; Zhang, Y.; Wang, J. *Chem. Commun.* **2015**, *51*, 11233.

(11) For the details of reaction condition optimization, see the Supporting Information.

(12) For reviews on furan, see: (a) Hou, X. L.; Cheung, H. Y.; Hon, T. Y.; Kwan, P. L.; Lo, T. H.; Tong, S. Y.; Wong, H. N. C. *Tetrahedron* **1998**, *54*, 1955. (b) Keay, B. A. *Chem. Soc. Rev.* **1999**, *28*, 209. (c) Brown, R. C. D. *Angew. Chem., Int. Ed.* **2005**, *44*, 850. (d) Kirsch, S. F. *Org. Biomol. Chem.* **2006**, *4*, 2076. (e) Moran, W. J.; Rodríguez, A. *Org. Prep. Proced. Int.* **2012**, *44*, 103. For recent examples, see ref 6 and also: (f) Wang, T.; Shi, S.; Hansmann, M. M.; Rettenmeier, E.; Rudolph, M.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2014**, *53*, 3715. (g) Wang, T.; Huang, L.; Shi, S.; Rudolph, M.; Hashmi, A. S. K. *Chem. - Eur. J.* **2014**, *20*, 14868. (h) Xia, Y.; Xia, Y.; Ge, R.; Liu, Z.; Xiao, Q.; Zhang, Y.; Wang, J. *Angew. Chem., Int. Ed.* **2014**, *53*, 3917. (i) Wang, T.; Shi, S.; Rudolph, M.; Hashmi, A. S. K. *Adv. Synth. Catal.* **2014**, *356*, 2337.

(13) Journet, M.; Cai, D.; DiMichele, L. M.; Larsen, R. D. *Tetrahedron Lett.* **1998**, *39*, 6427.

(14) Bartoli, G.; Bosco, M.; Carlone, A.; Dalpozzo, R.; Galzerano, P.; Melchiorre, P.; Sambri, L. *Tetrahedron Lett.* **2008**, *49*, 2555.

DOI: 10.1021/acs.joc.5b01350
J. Org. Chem. 2015, 80, 7856−7864